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Investigations of fml profile buckling and post-buckling behaviour under axial compression

D. Banat, Z. Kolakowski, R.J. Mania *

Department of Strength of Materials, Lodz University of Technology, Stefanowskiego 1/15, 90-924 Lodz, Poland

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The buckling and post-buckling behaviour of thin-walled Fibre Metal Laminate (FML) profiles subjected to axial loading is discussed. Study concerns open cross-section profiles which consist of alternating thin layers of aluminium and fibre-reinforced unidirectional prepreg. Laboratory tested specimens were manufactured by autoclaving technique. Depending on fibres alignment, various 3/2-layer stacking were considered and subjected to axial compression in buckling tests. Carrying out an experiment allowed one to determine buckling load and equilibrium paths in buckling and post-buckling state. The results of substantial experimental investigations were compared with FML panel/columns modelling in FEA and with analytically examined based on Koiter's asymptotic theory. In conducted experiments the careful design of simply support boundary conditions of loaded edges of thin-walled columns is examined and discussed. Detailed analysis was also performed to assess the influence of the various fibres alignment on the specimen buckling and post-buckling response.

1. Introduction

Advanced structural materials in almost all branches of industry are currently greatly associated with thin-walled composite structures. A wide group of composites is represented by Fibre Metal Laminates (FMLs) constructed by binding fibre-reinforced laminates with metallic layers. Furthermore, at present most of the FMLs applications are based particularly on unidirectional glass fibre-reinforced prepregs combined with aluminium alloys sheets (GLARE type). Such lightweight materials are crucial for advanced aerospace structures [1,2]. Major advantage of fibre-reinforced composites over other structural materials is improved strength and stiffness, particularly when compared on a unit weight basis. Furthermore, unidirectional composite can be used in specific loading conditions, depending on fibres alignment what can be achieved by so called 'tailoring' approach [15]. Multiple fibres alignment is used to achieve the proper balance of strength and stiffness which is necessary to withstand loads from different directions [3,4].

In practice, it is relatively hard to build the composite consisting of specific material layers. Hence, during last few decades numerous research was performed on etched aluminium and on adhesive bonding properties [5]. Inappropriate material connection can cause huge residual stresses or spatial voids in its structure. Combining, for instance, aluminium with carbon fibres causes significant difficulties with galvanic corrosion [6]. Therefore, for FML application with aluminium constituent, glass fibres are most commonly used. GFRP are by the way composite materials of the industrial consumption exceeds 2.6 million tons [7].

The application of FML type hybrid material structures - especially in aviation, was resolved due to their excellent fatigue properties. This property as well as damage tolerance are also continuously assessed in order to increase the material fatigue resistance - still the one of the most important material property of hybrid laminated composites [8]. Nonetheless, such outstanding structural and utility property - when considered from stability of structure point of view, could be seen as a disadvantage. Higher fatigue crack growth resistance makes lower thickness and/or higher stresses in fibre-reinforced laminates possible which suggests that thin-walled sections may undergo different modes of buckling. Furthermore, their failure mechanisms are rather complex due to their inhomogeneous structure, composed of constituents with significantly different properties that remain distinct in the final composition.

Considered in the paper FML panel/columns are classical thin-walled members thus in terms of their strength and stiffness assessment the problem of buckling is a significant matter and mostly not a strength but a stability resistance of the structure dominates the analysis. Additionally, the failure criteria application that evaluate material ability to withstand an applied load without failure [9] should be employed within the structural assessment. Such a stability issue has always been one of the main field of scientists' interest and various analysis were performed to

* Corresponding author.

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study static buckling of FML thin-walled structures [10,11]. However, the list of publications devoted to the buckling and post buckling of thin-walled FML panels is limited. In general, buckling tests of composite thin-walled members performed in laboratory are compared with FEA and based on that optimising analysis might be conducted. This approach of mutual influence of experimental and analytical stability investigations is present in few papers [12–14] were semi-analytical method used to validate the results in buckling and post-buckling state is employed. In that approach, the FEA examines the nonlinear stability of the structure in the post-buckling state, wherein specific local buckling mode is forced to ensure stable behaviour.

Numerous analyses of thin-walled columns have also compared buckling behaviour of variety of complex open cross-sections profiles/columns and different fibres alignment [15,16]. Some preliminary analysis to current FML buckling study is given in Refs. [17], where various columns shapes, selection of material constituents and experimental procedures are discussed. Nonetheless, it is obvious that real structures have usually even small imperfections in comparison to the ideal ones, hence it was proved that the results obtained from the experiment differ to some extent from the theory and analytical solution [18].

Thus in the scope of survey presented, despite the practical and structural importance of FML thin-walled panels, their research in the area of the buckling and post-buckling range still requires further analysis and verification of its tools. The numerical simulations and analytical modelling employ different theories and approximations which generally can be verified and validated in the way of careful experiments. To improve and develop these methods of research our multi-approach investigations of FML panels were undertaken.

2. Subject of the study

Studies were undertaken to investigate thin-walled columns of Z-shape and channel cross section, both produced by the autoclave method at the Lublin University of Technology (LUT) [19]. The literature surveys indicate that changes in processing parameters of autoclave method can significantly influence the strength and stability behaviour of the composite material (see for example [19–21]) therefore the manufacturing process requires a great care.

Both channel section and Z-shape section profile/columns have the same overall dimension: the width of the web – 80 mm, flange – 40 mm, column length ca. 300 mm and corner radius (R) between the web and the flange approximately 1.75 mm (Fig. 1a,b). For all FML profiles the 3/2 configuration with symmetrical lay-ups with respect to wall midplane was investigated. Here '3' means three metallic layers and '2' refers to two embedded composite layers which are doubled and consist of two unidirectional GFRP prepregs (Fig. 1c). Metallic layer in analysed FML panels is an aluminium alloy 2024-T3 and for composite plies glass-epoxy unidirectional fibre reinforced prepreg TVR 380 M12 26% R-glass was applied. The nominal volume fraction of the fibre in prepreg equals ca. 60%, whereas the thickness of a single layer equals 0.3 mm for aluminium and 0.25 mm for prepreg, respectively. Depending on fibres alignment 7 various stacking sequences of FML were also considered (see Table 1).

Material properties of aluminium and glass-epoxy prepreg constituents were declared by specimens' manufacturer [19,20]. For the purpose of this study within numerical and analytical solution, only specific mechanical properties (Table 2) - later referred as 'LUT' data, were adopted in the main orthotropic directions connected with fibre orientation (principal 1-axis). The composite material plies were designated to the properties in a plane stress state, however, their orthotropic behaviour was defined for three dimensional model in FEA according to specific rules [22]. Therefore implementation of real mechanical properties in numerical modelling allows the results comparison with experimental data.

3. Preliminary experimental procedures and boundary conditions adjustment

Experimental tests of compressed FML thin-walled short columns were performed using an universal electromechanical strength testing machine of Instron (load range 200 kN), upgraded with Zwick/Roel control software. The machine was equipped with custom plate rigs designed to ensure that FML column specimen was loaded axially and assumed boundary conditions were uniformly reproduced along profile loaded edges. The tests were performed under standard conditions at a room temperature of 23 °C and steady cross-beam velocity set to 1 mm/min. Applied screw type testing machine provided displacement control loading. Therefore, comparatively smaller displacement and less rapid failure can be achieved than for load control hydraulic testing machine. Nonetheless, the specific type of loading control does not affect the buckling itself [23].

In order to prevent lateral displacement of the loaded edges, various simply supported conditions were considered [16,18,24]. Though, it should be emphasised that recalled experiments were dedicated mostly to a simple FML thin-walled specimen test of complex plate structure. Therefore, a very often used solution - V-shaped design 'knife-edge' [25] was considered at first. Some examples of this solution of simply support boundary condition are presented in Fig. 2 according to [25].

Nonetheless, such solution was rejected as it could provide significant shearing in composite layers and any machining of hybrid composite panel edges could be a source of delamination. Bearing that in mind and taking into consideration aforementioned literature hints, the simply support boundary condition was reproduced by a flat bottom groove with slightly chamfered edges of 2 mm depth in total. A small clearance was left when compared with profile wall thickness, i.e. approximately 0.5 mm in groove

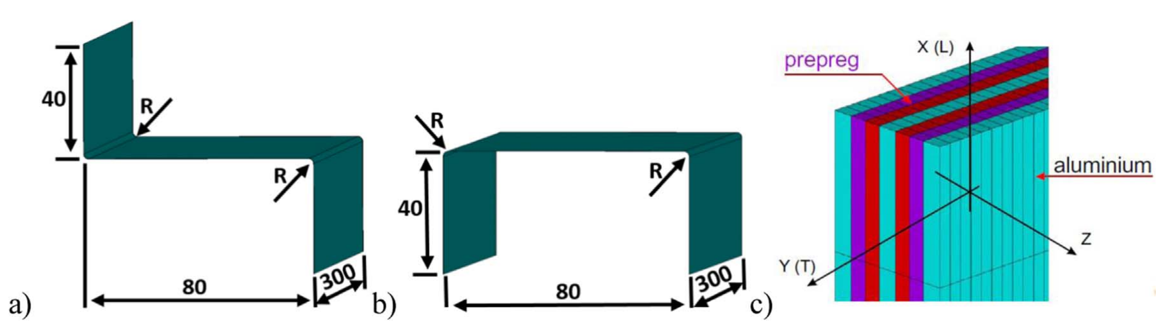

Fig. 1. Overall dimensions of Z-shape (a) and channel section (b) with specific lay-up configuration (c).